

AMBER at CERN - Apparatus for Meson and Baryon Experimental Research

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The AMBER collaboration, approved by the CERN SPS Committee as north-area experiment NA66, pursues a broad programme in hadron structure and hadron spectroscopy using a versatile spectrometer setup at the CERN SPS M2 beam-line.

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AMBER (NA66) is a recently approved fixed target experiment at the M2 beam-line in the North Area of CERN. It is a newly formed collaboration following from the successful COMPASS collaboration, which had used the same beam-line.

AMBER Physics Motivation

The physics programme of AMBER is driven by the question of the nature of the major part of visible matter, which is formed by the hadrons inside the nuclei of single atoms up to the giant structures in stars. Hadrons have many features that can be well explained by a substructure of quarks and gluons, which are the fundamental particles of the theory of quantum chromodynamics (QCD). While this theory is well-defined in principle, real-life calculations are in some regards difficult and accurate predictions, based on the first principles of QCD alone, are not available in many aspects of how these fundamental particles form stable or almost stable hadrons. Most prominently, it is not clarified how hadrons acquire their mass by the binding of the almost massless quarks and gluons, and how the large difference between the ground-state baryon and meson masses comes about. This basic question about the *Emergence of Hadron Mass* (EHM) is linked to the mechanism of dynamical breaking of the chiral symmetry of QCD. This mechanism assumes the light mesons, pions and kaons, to be massless in the chiral limit – they are the respective Goldstone bosons – and their mass is connected largely to symmetry breaking, while the baryon masses are much less affected by this mechanism. Beyond the proton being about seven times heavier than the pion, there are many more intriguing observations in the properties and interactions of hadrons. They are reflected, in the partonic picture, in the structure functions for quarks and gluons, which are studied for nucleons through deep-inelastic scattering and for mesons best in Drell-Yan processes. In the integral view of hadrons, the nature of the binding of the partons determines ultimately the size of the hadrons, reflected in their charge radii, and other properties such as their polarisabilities. The mechanism of how the quark-gluon binding leads to those observable quantities, is intimately linked to the understanding of EHM and thus, how QCD is responsible for the observable properties of hadrons. The planned AMBER measurements aim to deliver many new experimental constraints to achieve a better knowledge on how the hadron masses and other hadron properties emerge.

AMBER Collaboration and Physics Programme at the CERN M2 Beamline

The AMBER collaboration consists of more than 35 institutions worldwide, reflecting the wide-ranging physics interest in its unique capabilities. The main spectrometer follows and reuses largely the existing COMPASS spectrometer, with additional targets and detector systems added to meet the current and future needs of the new physics programme. This rich programme is starting in 2023 and will last for well over a decade to realise.

AMBER will make use of the versatile beam delivery available at the M2 beam line. This beam line is fed by the SPS proton accelerator and a production target providing muon, proton, pion and kaon beams of both charges with energies ranging from 50 GeV up to 280 GeV.

The physics programme consists of a variety of topics in hadron structure and spectroscopy, making best use of the versatile beams and flexible target configurations. It is divided into two phases, the second phase aiming for much higher beam intensities for meson beams.

AMBER Phase-1

The approved first phase of experiments will address three main physics questions: First, the size of production cross sections for antiprotons off Helium targets using proton beams, to be determined with high precision over an energy range from 50 GeV to 280 GeV. This is a crucial

input for dark matter searches. Second, in the context of the proton radius puzzle, the measurement of the proton charge radius following the form-factor method with a high-energy muon beam of 100 GeV. Third, the pion and kaon parton distribution functions (PDFs), which will be accessed through Drell-Yan and charmonium production measurements using both negatively and positively charged meson beams with an energy of 190 GeV.

Antiproton production cross sections

Observations of the relative motion of the galaxies and their rotation curves point to the existence of large amount of matter not emitting e.m. radiation but producing a relevant gravitational pull. This dark matter seems then to occupy large “halos” around the visible part of the galaxies. Measurements of large-scale structures of the universe and of the cosmic microwave background (CMB), converge to a model where the dark matter (DM) represents more than 95% of the universe matter content and indicates that this DM is completely different from what we know. The CMB observations point to the fact that dark matter must be electrically neutral, massive, and non-baryonic. This de facto excludes all the known elementary particles. The nature and origin of the dark matter represent one of big unknowns in our understanding of the universe.

Anti-protons are naturally expected in the cosmic rays, that in general are instead dominated by the proton and helium nuclei components. They are produced when protons and He collide with the so called Inter Stellar Medium (ISM), which in turn is mostly made of protons and He nuclei. These collision of the type p-p, p-He, He-p and He-He produce all sorts of elementary particles that stay within the cosmic ray flux as consequence of their kinematics. The heavier particles eventually decay, so that antiprotons in cosmic rays are either directly produced in the interactions or stemming from the decay of other particles. Overall, antiprotons represent a cosmic-ray fraction of 10^{-4} with respect to protons. Antiprotons can also originate from the annihilation or decay of dark matter particles. These DM-originated antiprotons might be sufficiently abundant to produce a visible additional component to the one from ISM collisions. This scenario is a classical particle physics situation, where the ISM antiprotons represent the background over which we search for possible DM signals.

AMS-02 has produced a very accurate measurement of the antiproton flux up to 400 GV rigidity and current uncertainties in the standard nuclear physics production cross sections are a dominant source in the prediction of the expected antiproton ISM background. Several interesting measurements have been done recently, which include antiprotons from p-p collisions at CERN SPS energies (NA61) and p-He at several TeV using the LHC beam (LHCb). However, there is a substantial lack of knowledge of the antiproton production cross sections from p-He collisions at CERN SPS energies (50 to 300 GeV). Considering that p-He produce roughly 40% of the cosmic ray ISM antiprotons, this represents a significant uncertainty that is important to be reduced.

AMBER will perform precise antiproton production cross section measurements from a secondary proton beam impinging on liquid helium target with beam energies ranging from 50 to 280 GeV. The AMBER spectrometer allows for a full reconstruction of the interaction events and its RICH detector allows for the identification of antiproton tracks. AMBER will provide a double differential (momentum and direction of antiprotons) cross-section measurement at four proton beam energies in the range from 50 to 280 GeV; that is in the kinematic range where current AMS-02 data suffer most from nuclear cross section uncertainties.

Proton radius

Understanding the size of the most fundamental baryon, the proton, is a crucial measurement in hadron physics and beyond. It is known for more than a decade that measurements using electron scattering to extract the proton's electric form factor and extrapolating it to the real photon point are in disagreement with high precision spectroscopic measurements using normal and muonic hydrogen atoms. Various experiments and methods in electron scattering have been performed, are still ongoing or planned to shed light on the problem. One measurement, namely

scattering high-energy muons off protons in order to extract the proton form factors, has yet to be performed.

In view of different methods leading to contradictory results for concluding on the proton radius, it is decisive to perform measurements with different systematics. High-energy muon scattering turns out to be promising in that regard, since they have a minimal and well-controlled soft-scattering interaction when passing matter, and along the scattering process of interest, radiative effects are much smaller than for electrons.

Pion and kaon parton distribution functions

The third pillar of the AMBER phase-1 program is primarily devoted to the determination of the light pseudoscalar meson PDFs. This goal will be achieved through measurements of pion and kaon-induced Drell-Yan processes and charmonium production with detection of a muon pair in the final state. The two reactions are complementary: at leading order the Drell-Yan process proceeds through QED, whereas the charmonium production takes place only via QCD.

Therefore, the former is sensitive to the valence and sea quarks in the incoming particle, whereas the latter probes also its gluon distribution. AMBER will make use of hadron beams of negative and positive charge available exclusively at the CERN M2 beamline. Since these beams consist of mostly pions and a small fraction of kaons, AMBER will be able to simultaneously determine both pion and kaon PDFs.

The large statistics expected for the pion Drell-Yan measurements will lead to an improved determination of the valence quarks distribution. In addition, a combined analysis of the positive and negative Drell-Yan data will allow, for the first time, a clean extraction of the sea quarks distribution. Alternatively, the essentially unknown gluon distribution in the pion will be inferred using the complementary measurements of the charmonium cross sections.

The unknown kaon PDFs will be investigated at the same time as the pion PDFs by identifying the kaon component in the positive and in the negative hadron beams. The negative beam Drell-Yan data will be employed to determine the kaon valence PDF, although with somewhat limited statistics. A combined analysis of the negative and positive kaon data should provide a first look to the kaon sea distribution. With its much larger hadronic cross section, the kaon-induced charmonium production becomes particularly attractive. Moreover, the difference between the negative and the positive kaon-induced charmonium cross sections provides a direct and model-independent access to the valence antiquark distribution in the negative kaon. In addition, it freezes the quark-antiquark annihilation component of the cross section, so that the remaining fraction of the cross section is solely related to the kaon gluon distribution.

The pion and kaon PDF studies will be complemented with measurements of the lepton angular distributions. The charmonium polarization data is particularly sensitive to the shape of the meson PDFs, whereas the meson-induced Drell-Yan process at the forward rapidity region can be used to determine the meson distribution amplitudes (DAs). Theoretical calculations for the DAs do exist, but the useful Drell-Yan data are quite sparse.

The pion and kaon distribution amplitudes will be further investigated through diffractive dissociation of the meson into di-jets. As light front wave functions of mesons, the DAs are of fundamental importance for understanding the meson structure. While closely related to the meson valence-quark PDFs, the meson DAs are accessible via different physics processes. A direct measurement of the pion DAs was reported in the detection of di-jets in diffractive dissociation with a 500 GeV pion beam at Fermilab, although the interpretation of these data is still uncertain. New di-jet production data at AMBER are essential for understanding the Fermilab pion data and for extending the measurements of DAs to kaons.

Hence, the uniqueness of the meson beams with both polarities available at CERN puts AMBER into a world-leading position for the study of the structure of the charged pions and kaons. The

inclusive measurements of lepton pairs combined with the expected high statistics will significantly improve our knowledge of the quark and gluon content in the two lightest mesons, as a function of its parton momentum fraction and its transverse momentum. Complementary meson PDF measurements are also planned at JLAB and EIC, however they rely on the theoretical understanding of the Fock expansion and on the use of the Sullivan process, which makes use of the pion cloud around nuclei.

AMBER Phase-2

SPS delivers a large variety of beams to the CERN North Area. In Phase-1, AMBER uses the muon, pion, kaon and proton beams with a variety of fixed target configurations, similarly to the preceding COMPASS experiment. In Phase-2, measurements are foreseen that make use of an upgraded M2 beamline, aiming at enriched and more intense kaon beams, for which two options are discussed. The kaons in the existing M2 hadron beam may be separated by a radio-frequency method, allowing to dump the predominant pion and (anti)proton components. Since this does not increase the total number of available kaons, enhancements along the beamline allowing for a more intense hadron beam are also investigated. One of points to address with enhanced kaon beams is the continuation of the meson structure programme via the Drell-Yan process, as described above.

Prompt Photons

The kaon-induced prompt-photon production is an alternative way to access the quark and gluon structure of the kaon via the quark-antiquark annihilation and gluon Compton scattering processes as well as the inclusive production of neutral pions. These measurements are an important and independent complement to the DY and charmonia studies. Data taking with positive and negative kaon beams will help separating the two processes.

Meson-Photon Reactions in Peripheral Collisions with Nuclei

Similarly, the intense kaon beam delivered to AMBER will allow unique experiments in the spectroscopy of strange mesons and exploration of kaon low-energy parameters in ultra-soft collisions with nuclei, so-called Primakoff reactions.

Primakoff reactions give access to interactions of the beam particle with a photon from the electric field of the scatterer, here to kaon-photon reactions. Most prominently, with the elastic process, in which an outgoing photon and a kaon are observed, the kaon polarisability can be measured for the first time. Beyond that, in further final states including a neutral pion, or more pions or kaons, other aspects become accessible. In case of a single neutral pion, a low-energy coupling constant analogous to the chiral anomaly can be determined, the latter describing the coupling of three pions and a photon. For states with more mesons in the final state, a partial-wave analysis can reveal the contributing resonances and thus allows access to their coupling to the kaon-photon initial state, described by the radiative width of the resonances.

Hadron Radii

As indicated above, one of the physics programs of phase-1 of AMBER is the measurement of the proton radius in muon-proton elastic scattering. As for mesons such measurements cannot be performed in fixed-target kinematics, the alternative is to measure the elastic scattering of high-energetic mesons off atomic shell electrons in a fixed target. This technique has been used by previous experiments at CERN and Fermilab in the 1980s. AMBER will use the more intense kaon beams of the M2 beamline, combined with a modern readout system that allows to increase the statistics and the kinematic range of the measurement, and aims at determining the kaon charge radius with an about factor 10 better precision than currently known. Since the beam consists of a mixture of predominantly pions, kaons and (anti)protons, the measurement on the pion can be done in parallel with high statistics. At the same time, this opens the opportunity for a first determination of the radius of an anti-nucleus, namely the antiproton.

The Strange Meson Spectrum

For most of its history our understanding of hadron spectroscopy has been based around the quark model picture. In this, baryons are understood as combinations of three quarks, while mesons consist a quark and anti-quark pair. Our current experimental picture of hadronic states challenges the quark model expectations with both many missing and additional states that do not fit the model. From QCD inspired models beyond the baseline quark picture hadrons have been built with additional quarks and antiquarks; gluonic excitations; and states of pure gluons. The expectation is that if it is possible to construct such states via the strong interaction then they should appear in particle interactions in a similar manner to standard quark model hadrons and therefore be measurable providing an excellent test of non-perturbative QCD. Possibilities allowed within QCD beyond the quark model include tetraquarks, mesonic molecules, glueballs, and hybrid states.

Major experimental searches are underway at many international laboratories in an effort to provide sufficient constraints to unravel the structure of mesons. Strong candidates for glueballs and hybrids exist experimentally but the evidence is still not overwhelming, while in the light scalar sector the lightest nonet evades explanation from the quark model picture. Meanwhile advances from high energy experiments has re-woken interest in meson spectroscopy in the wider physics community. For example, strange mesons appear as resonances in multi-body hadronic decays of heavy mesons, which are under study in searches for CP violation or beyond standard model physics. The analysis of these decays often requires precise and complete knowledge of the appearing strange mesons as inputs.

Progress hinges on large, bespoke data sets with very small statistical and systematic uncertainties. The complexity of the problem necessitates a complementary approach featuring different production mechanisms as well as a multitude of complex final states, the analysis of which demands advanced analysis algorithms, reaction models and theoretical constraints. LatticeQCD has been the bedrock in predicting the spectrum of mesons and baryons, including hybrid and exotic states. Indeed, AMBER's predecessor, COMPASS, has been instrumental in establishing the experimental and analysis techniques to study these reactions and have been rewarded with clarifying the nature of a hybrid meson candidate, the π_1 .

The study of the light meson spectrum provides not only a deeper understanding of the strong interaction and its emerging phenomena, but also crucial input to understanding results in adjacent fields of physics, including the study of tetra quarks, CP violation and physics beyond the standard model.

AMBER aims to produce a world leading data set in the study of the light meson spectrum, focusing on the production of strange mesons through diffractive scattering of a high energy kaon beam. It will not only make use of the versatile beam configuration and excellent beam identification, but also improve the acceptance, efficiency and particle identification compared to its predecessors. AMBER aims to improve the sample size by a factor of 25 compared to the existing data sets.

Detector Developments

In terms of the setup, these new avenues of research require advances in the detection and identification of reaction products, mostly ionising charged particles at high fluxes and high rates. This in turn drives the development of the technology to measure ionising radiation, which is then readily translated into wider applications in industry, for governmental stake holders and healthcare applications. A case in point would be the development of novel particle identification detectors based on Cherenkov radiation using highly pixelated, high rate and high time resolution sensors for visible light photons which would find a wealth of applications in medical technology.